Stochastic 3D investigation of near-source motions from an underground explosion

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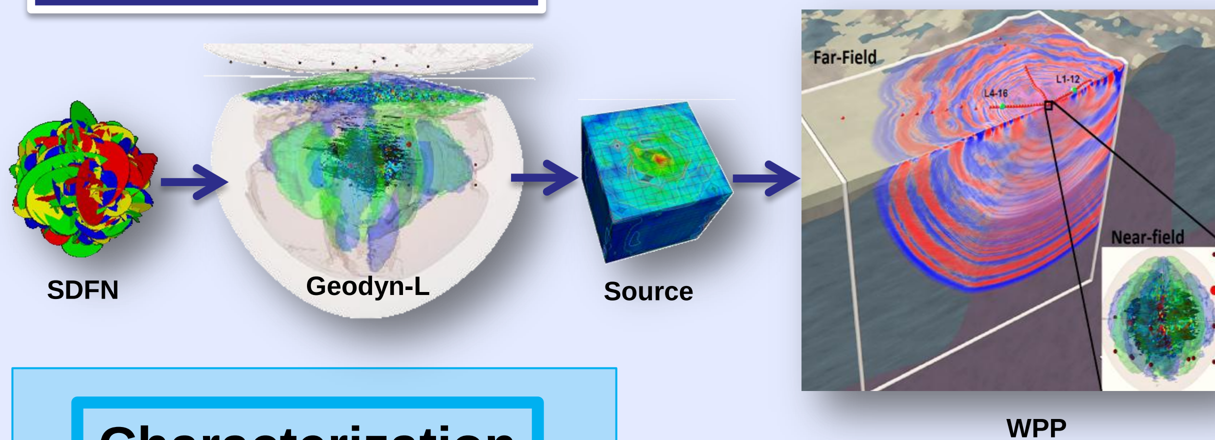
Uncertainty propagation throughout SPE designs, analyses, monitoring network and yield estimation

Three-tier analysis

Flow chart of UQ propagation and estimation for SPE



Characterization → SDFN → Geodyn-L → Near Field predictions

observations → Near Field predictions

Near Field predictions → Source → WPP → Far Field predictions

Characterization → SDFN → WPP

observations → Far Field predictions

Far Field predictions → Yield prediction

Far Field predictions → Monitoring design

Uncertainty Quantification enables us to make decision where /when characterization is limited

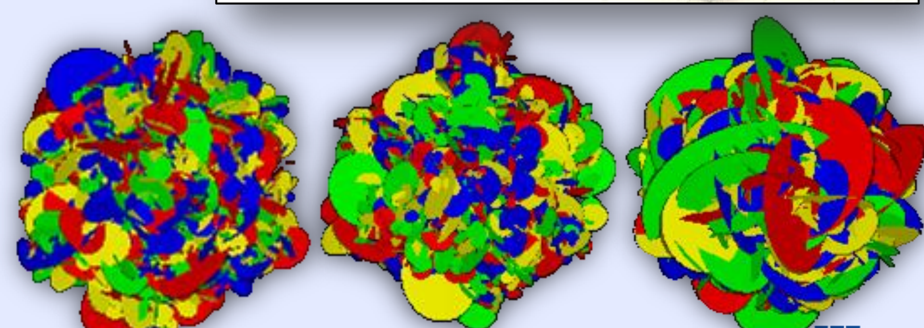
- **Uncertainties do exist in every walks of life**
  - It “cannot be eliminated” but minimized
  - Uncertainty is not essentially a “bad thing”
  - It enables make decision with margin of confidence

- **UQ use to be a very expensive task**
  - UQ is becoming relatively to moderately inexpensive
  - Nowadays, computational tools (hardware & software) are readily available
  - DOE Labs are at the leading-edge in UQ

- **Several sites of interest are of limited access and/or only “remote” characterization is available**
  - Monitoring underground explosion
  - Estimating yield and depth of sources
  - Probabilistic discrimination of explosives from EQs in jointed rock

Make decision w/ confidence

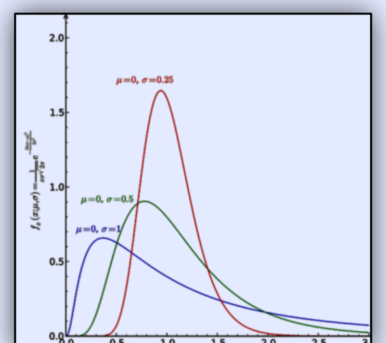
LLNL’s HPC



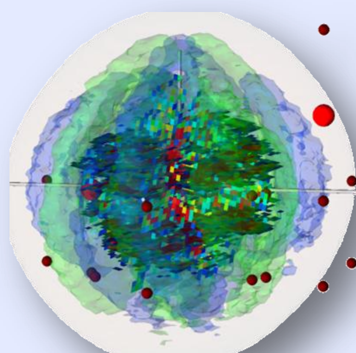
3 discrete fracture networks

Uncertainties exist in SPE from end to end: e.g. in data, conceptual and numerical models

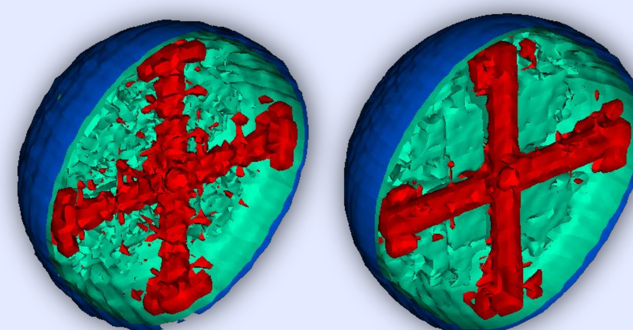
- **Aleatoric**
  - A SDFN is characterized by:
    - e.g. Statistical Models
    - e.g. Set of joints
  - Material properties
    - Scale disparity Measurements at laboratory scale may not be necessarily applicable to large scale
    - Intrinsic properties can vary spatially and temporally
  - Characterization is local but we need to ‘extrapolate’ between the wells
- **Epistemic**
  - Physics based uncertainty
  - Model “uncertainty”
    - Physics (discrete vs continuum)
    - Different codes ~ different outcomes
- **Measurements (direct or indirect)**



Statistical characterization

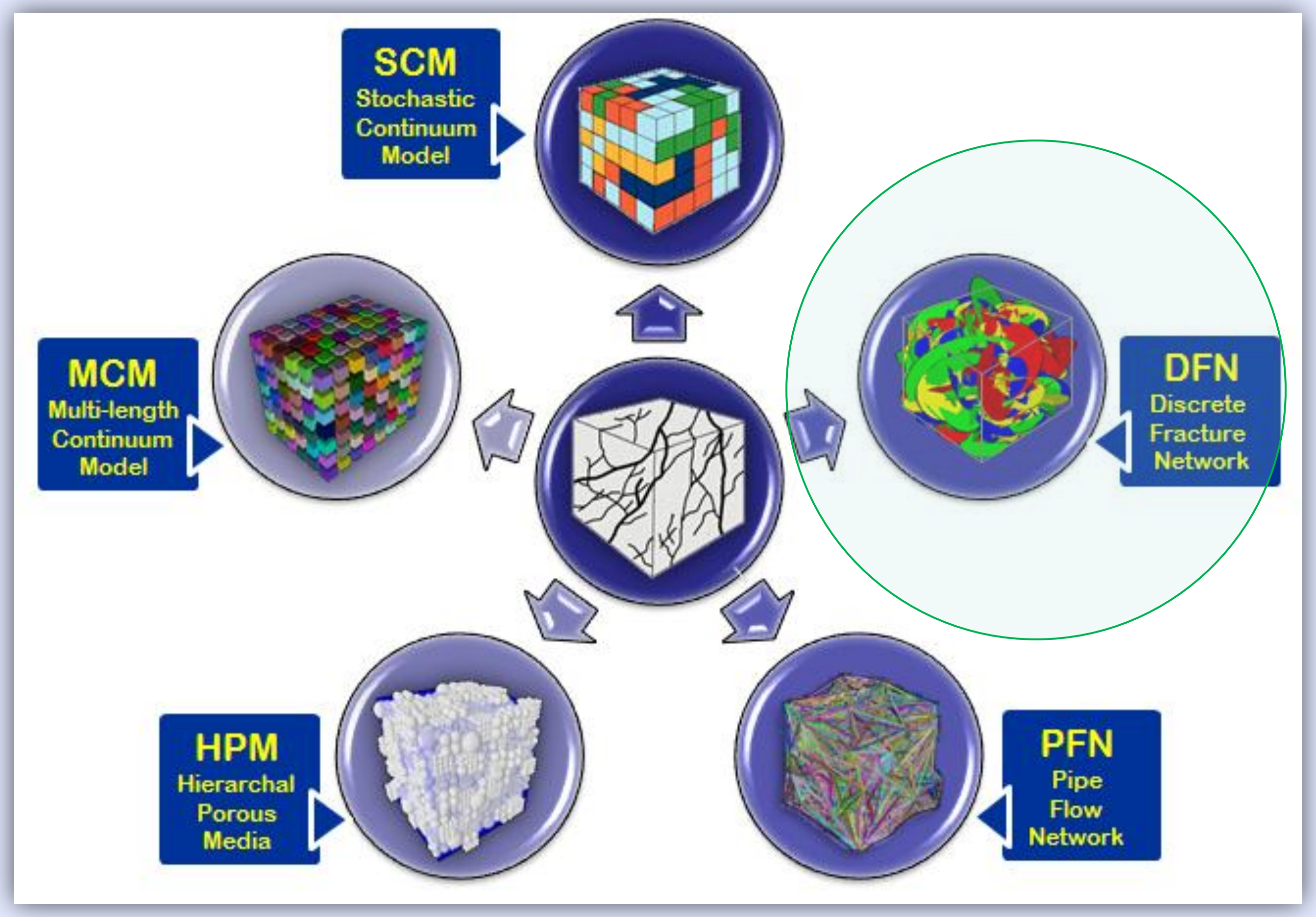


Multi-scale problem



Numerical simulations

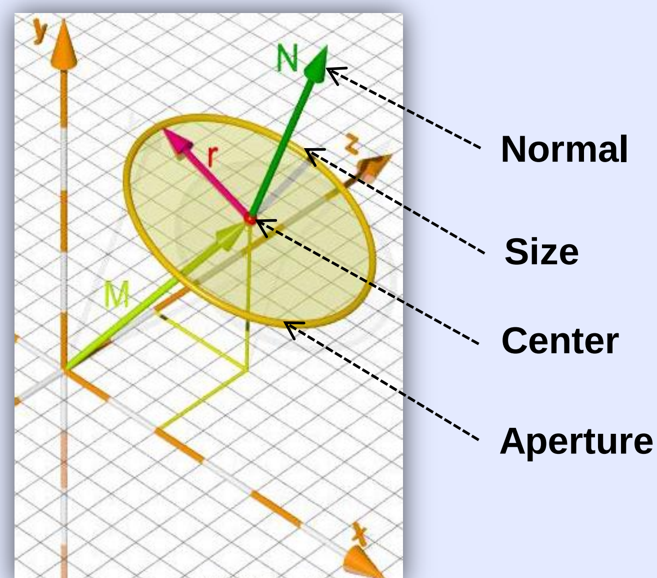
There are several approaches for representing joints, DFN is the most appropriate for SPE UQ analyses

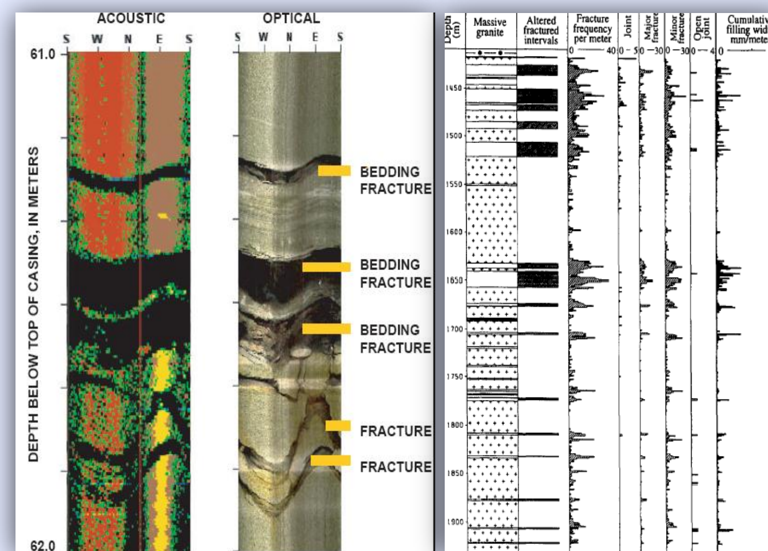


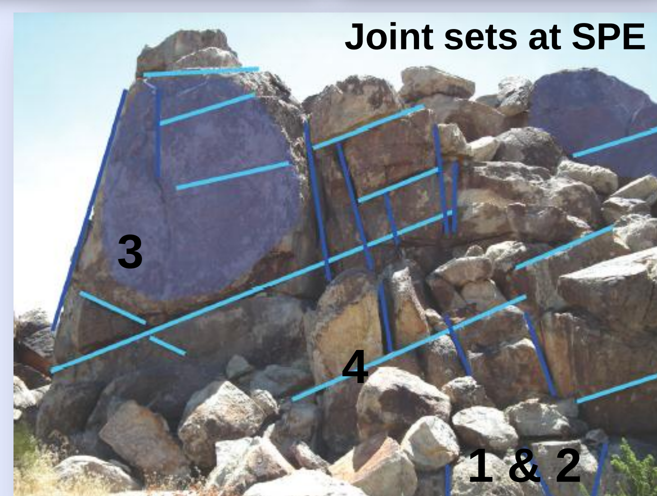
Discrete Fracture Network (DNF) approach offers unique capabilities to not only "mimic" in-situ fracture characterization but also to assess uncertainties, their propagation and quantification

Fracture (Joint) characterization in a stochastic discrete fracture network (SDFN) approach

- **In-Situ fractures are assumed**
  - random with a finite size
  - belong to different (sets) families

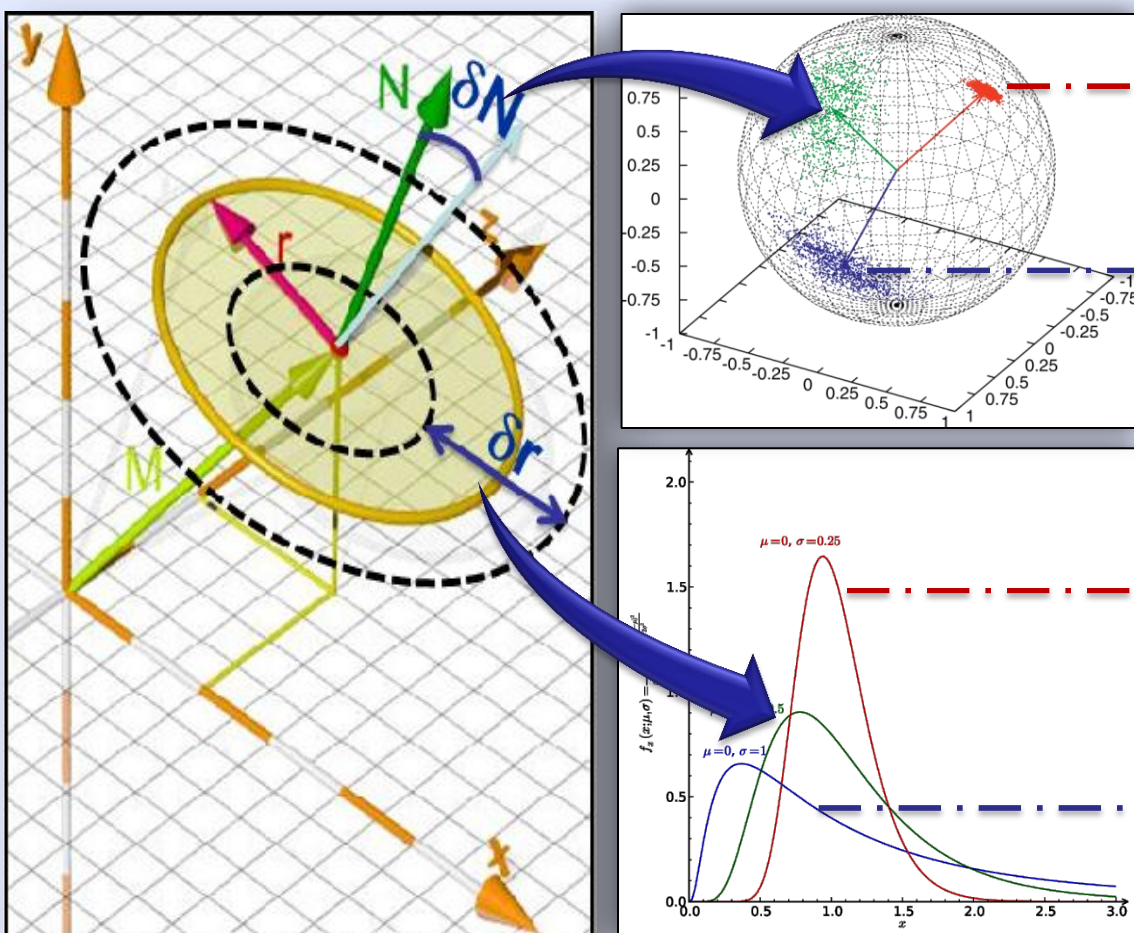




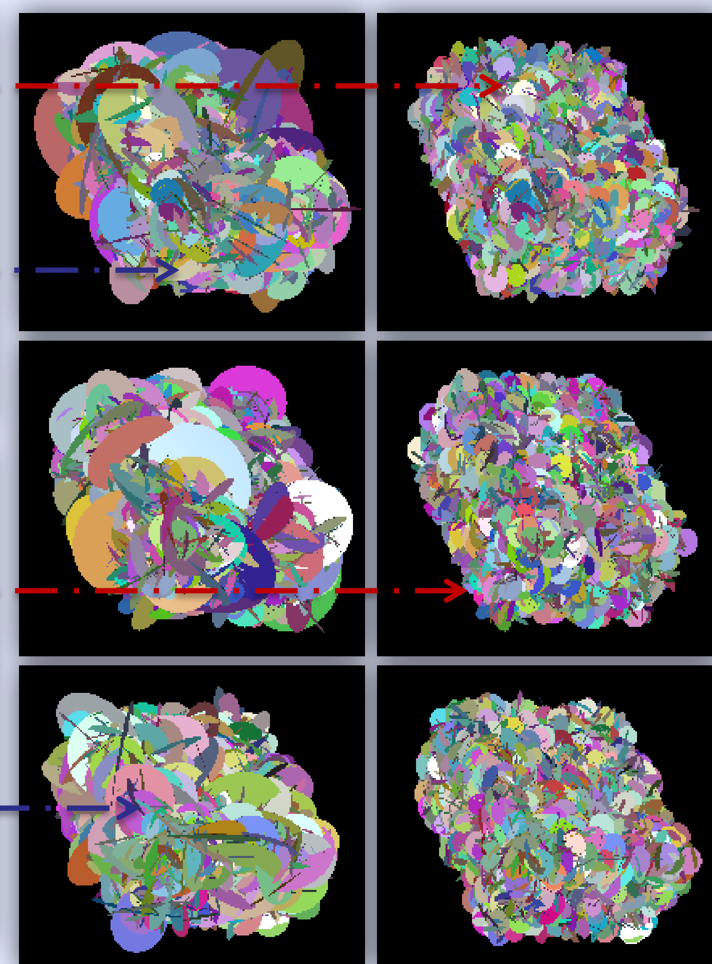


- **Each set of joints is characterized by:**
  - density, location of centers,
  - orientations, aperture & radius PDFs
  - PDFs are inferred from in situ characterization
  - In line with what is been conducted for SPE

Several parameters can be tuned to create equally probable SDFN with same statistics



Joint orientation and size can be tuned to create equally probable fracture networks (rock mass)

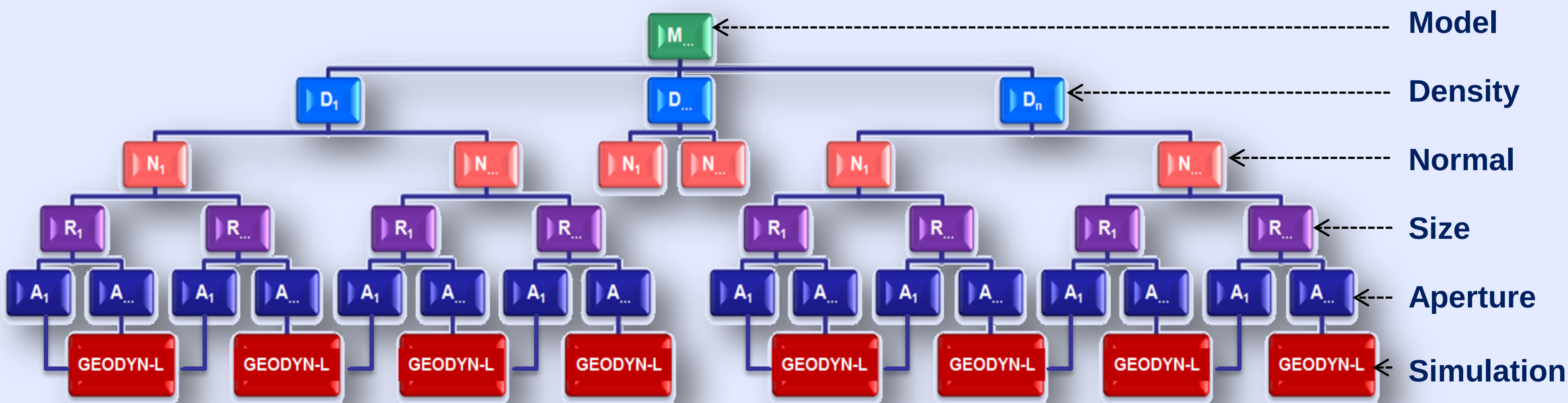


Example of three equally probable realizations with different statistical control on the size and orientation of the joints

WP in jointed rock mass is a highly non-linear problem, UQ is conducted using brute force Monte Carlo

- **"Geological" uncertainties:**
  - Statistical Models
    - Center Density
    - Orientation Density
    - Aperture Density
    - Radius Density
    - Fracture Geometry
  - Number of Fracture Family
- **"Geomechanical" uncertainties:**
  - Equation of state
    - Density, bulk sound speed..
  - Yield surface model
    - Tensile strength…
  - Porosity model
    - Friction, cohesion, compaction…

Large parameter space



Wave propagation with discrete representation of joints is CPU time cumbersome

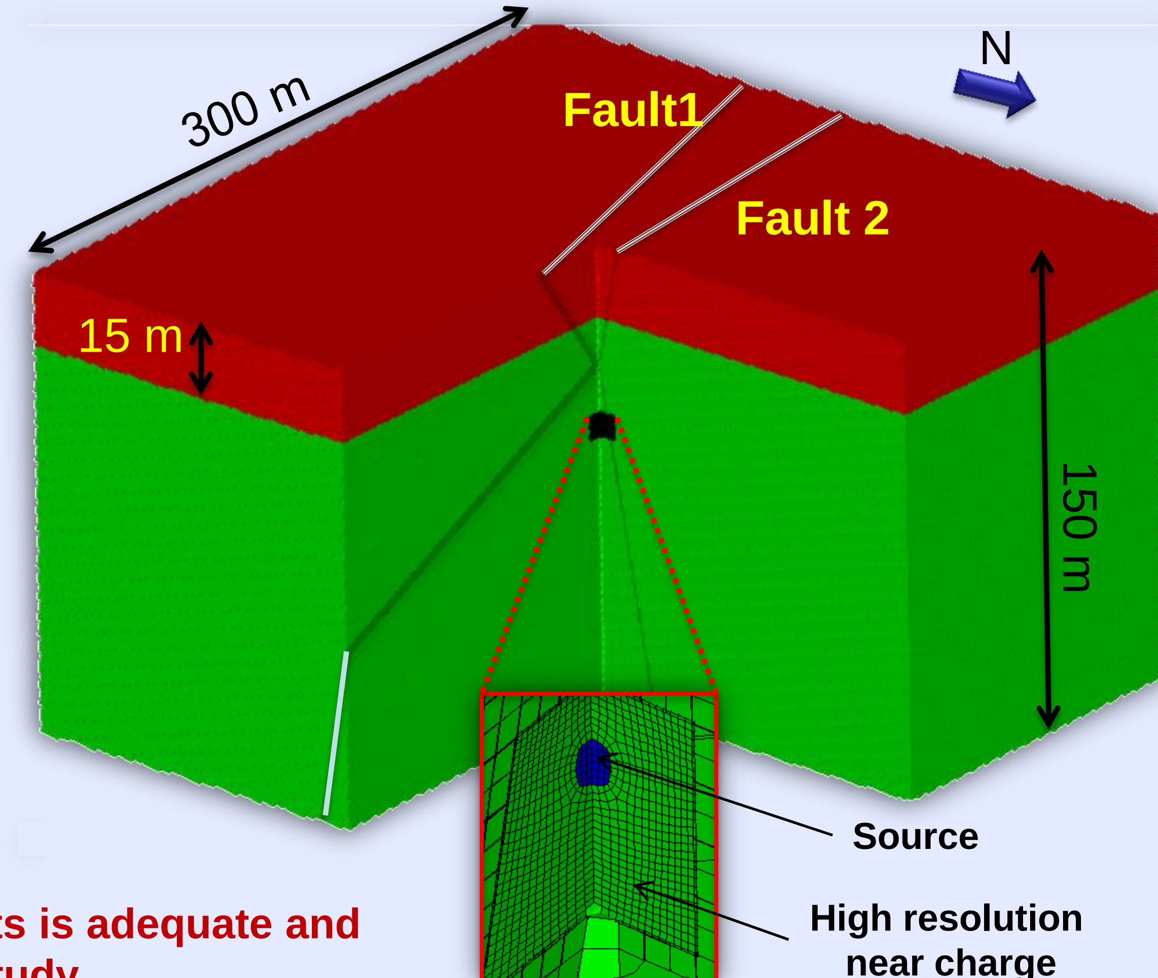
Typical physical dimension
- joint aperture ~1 mm
- joints spacing ~1 m
- source size ~1 m
- region ~300 m

Computational requirements
- ~20-50 million elements
- ~100-200 million zones
- **~3240 CPU for 12 hours**

Uncertainty quantification
- ~ 40 runs a set
- ~ 9 parameters
- **~ 200TB**

Judiciously conduct the UQ
- sampling effectively
- reducing model complexity

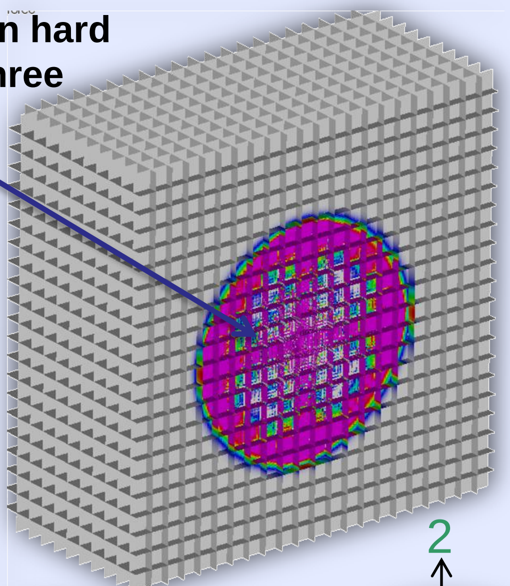
A prototype model for SPE3

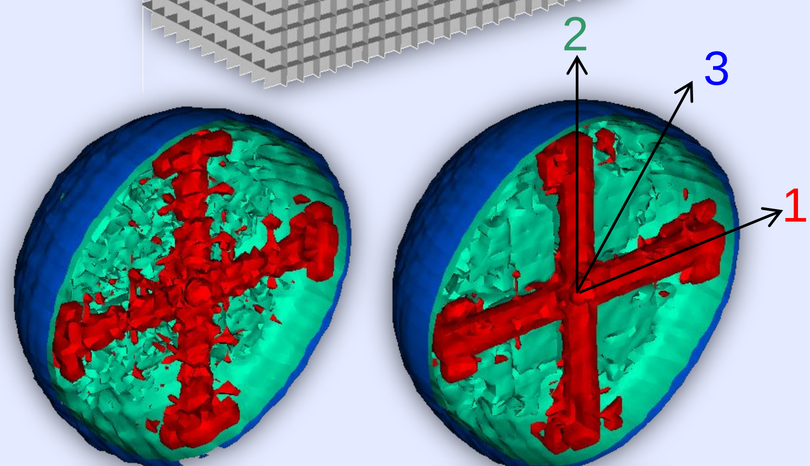


Continuum representation of joints is adequate and accurate for UQ and parametric study

Several cases where solved with discrete & continuum joint representation, both approaches show very similar results

Explosion in hard rock with three Cartesian sets of joints

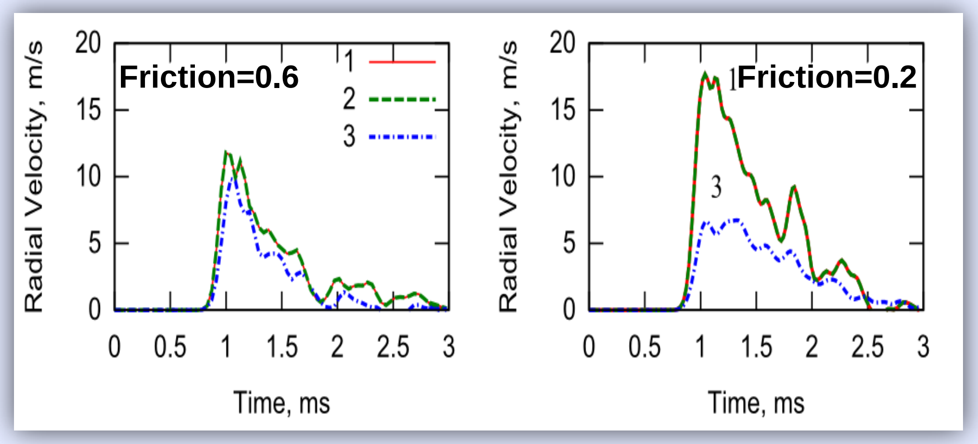




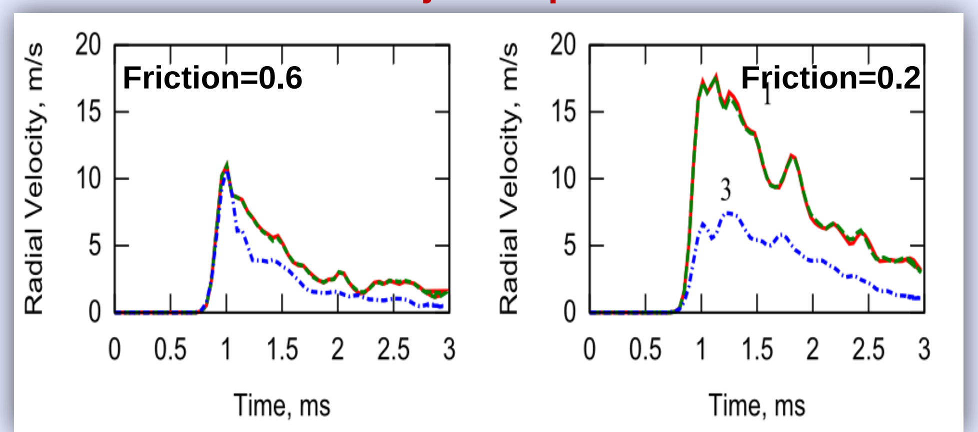
Discrete Continuum

Pressure contours (0-50 MPa)
Joint spacing 1 m, friction ~0.2

Discrete joint representation



Continuum joint representation

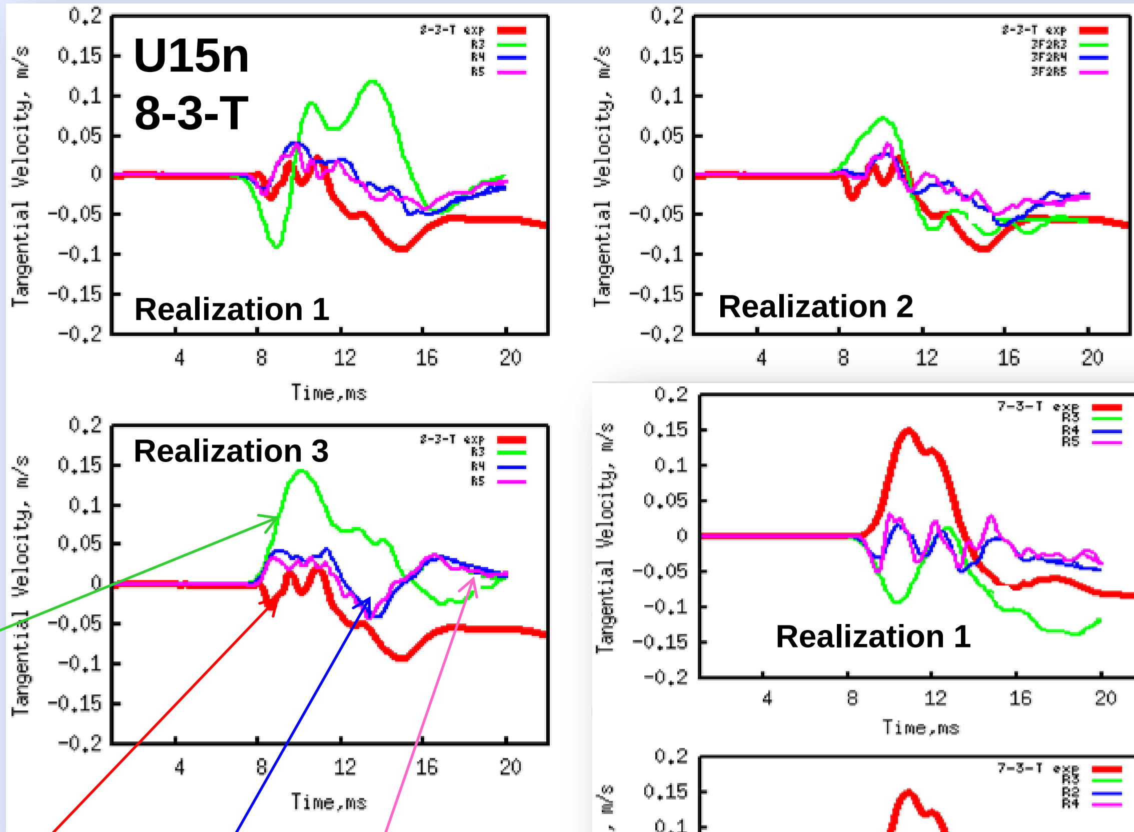


Dependence on joint friction

Continuum approach relies on meshing appropriately the joints, a mesh sensitivity analysis has been conducted

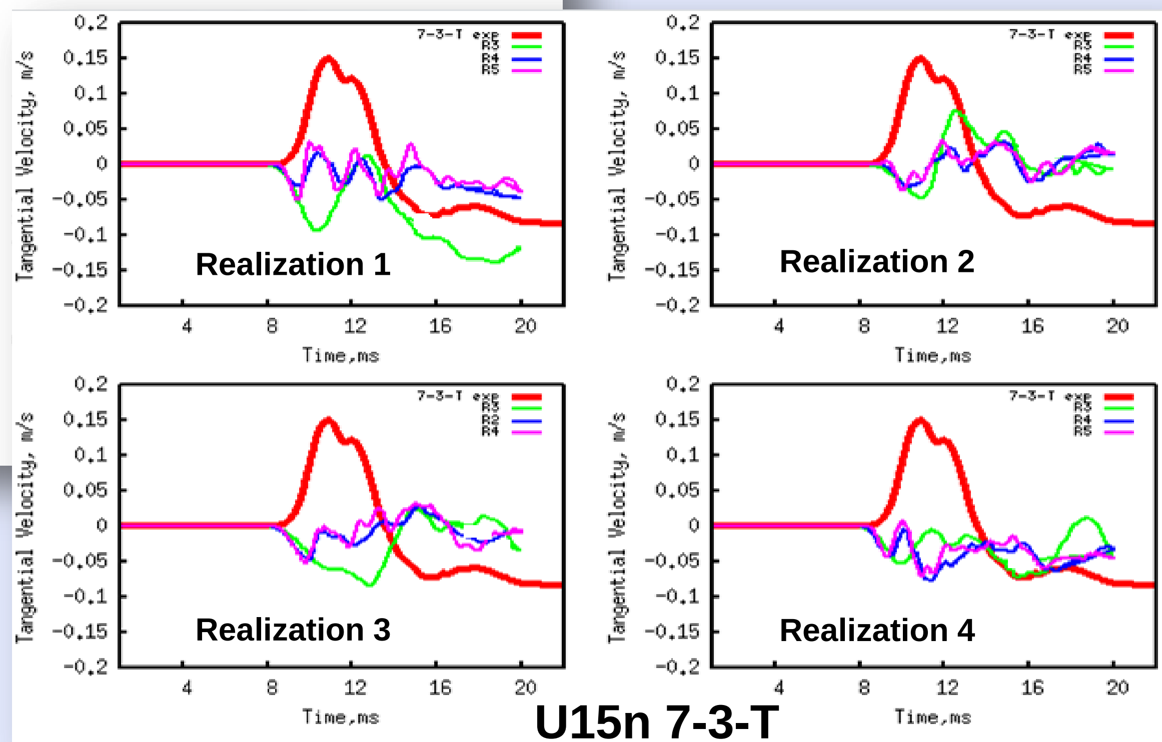
R3: 1-2Hrs 864 CPUs (x1)
R4: 2-4Hrs 864 CPUs (x4)
R5: 6-8Hrs 864 CPUs (x8)

R4 is a balance between accuracy and CPU-Hrs



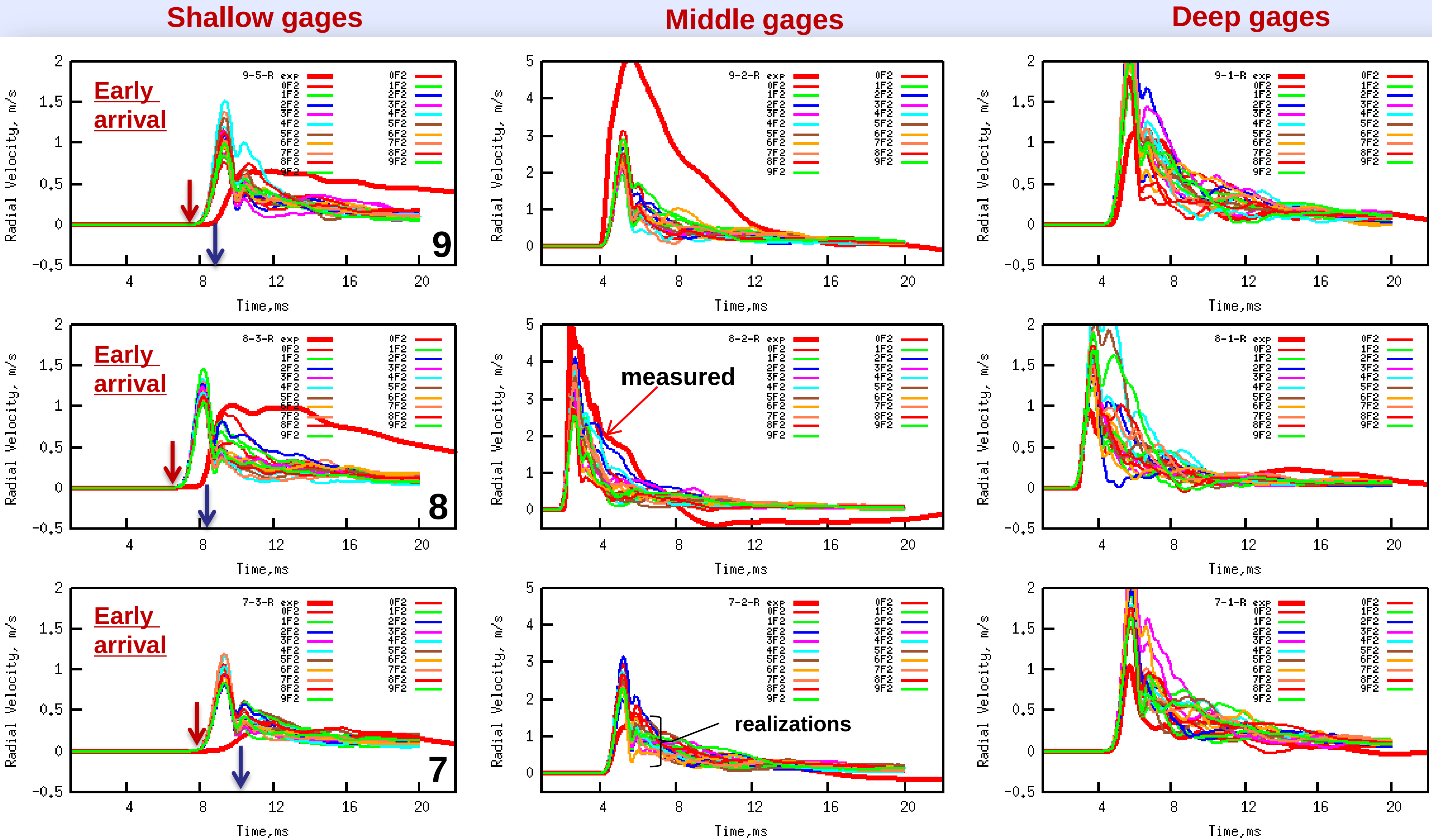
R3

Observed R4 R5



R4 & R5 are very similar and within 2% in average
R3 is distinctly different

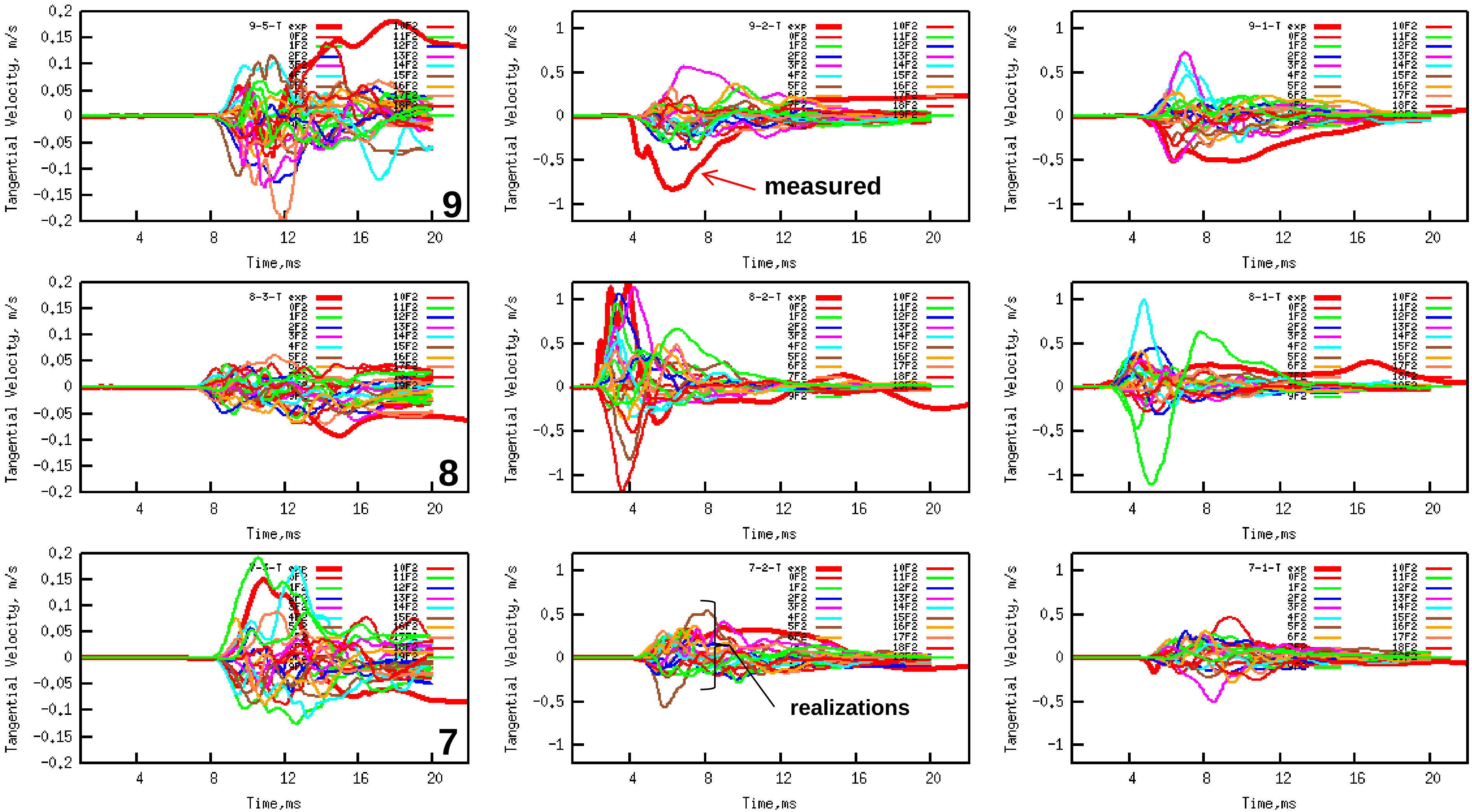
UQ analysis: single Layer model -- Radial velocity of 20 Monte Carlo simulations



Good coverage of velocities at middle and deep gages – discrepancies in arrival times at shallow gages

UQ analysis: single layer model – Tangential velocity of 20 Monte Carlo simulations

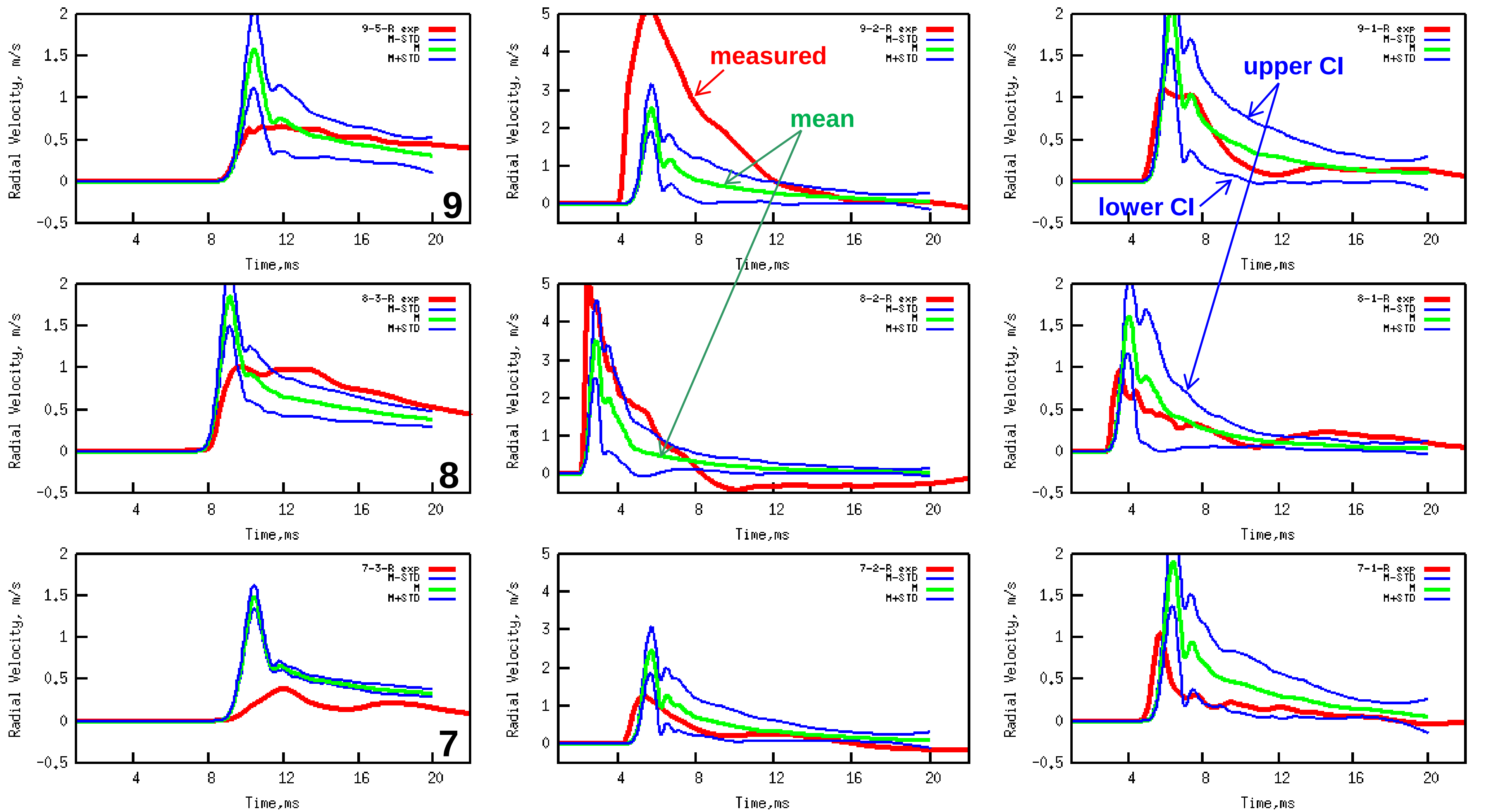
Shallow gages | **Middle gages** | **Deep gages**



Wide coverage of velocities at all gages – no apparent discrimination on the polarization

UQ analysis: double layer model – Radial velocity statistics based on 40 MCS

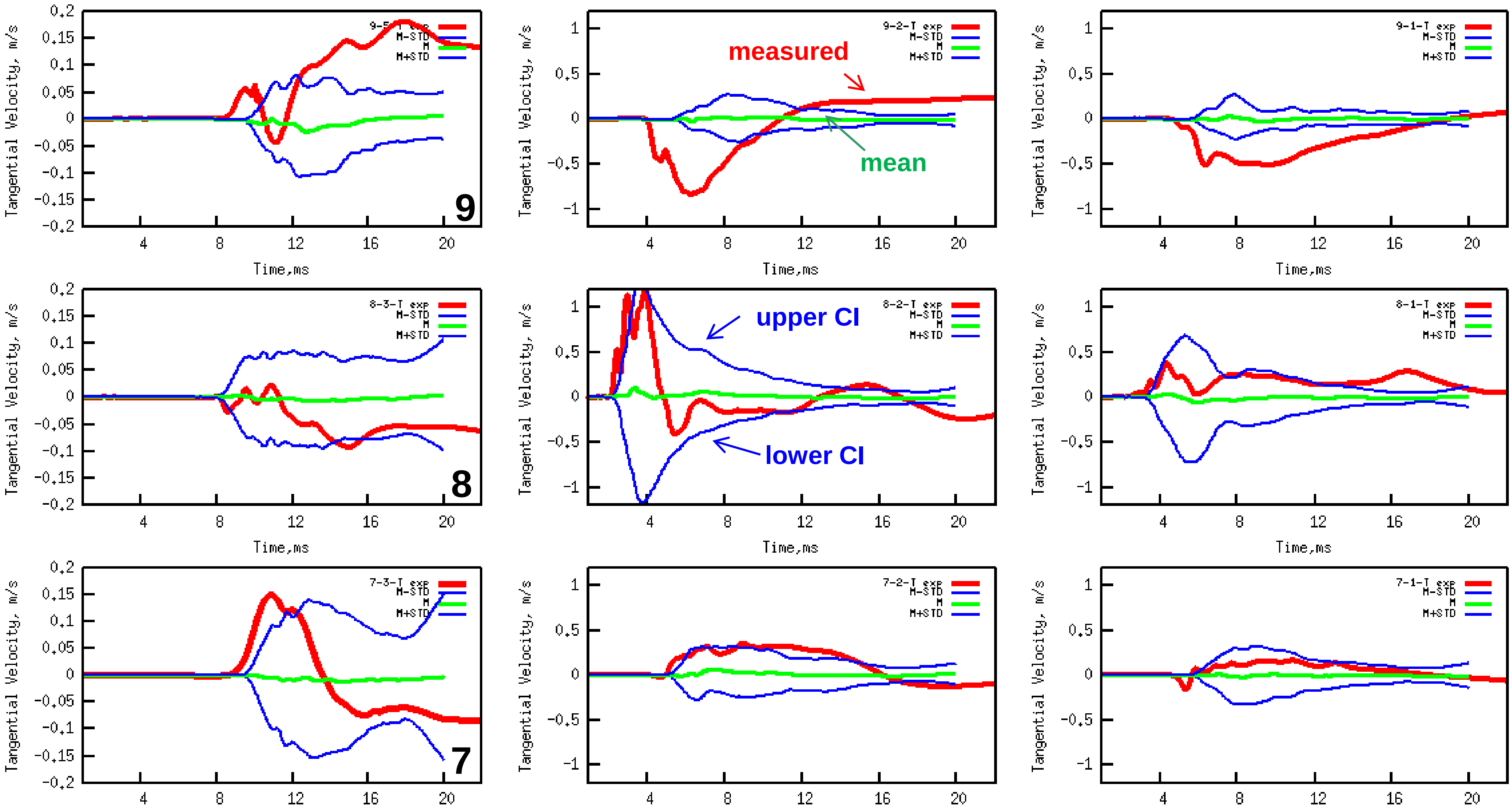
Shallow gages | **Middle gages** | **Deep gages**



Gage 9-2 is anomalous – Model over predicts peak velocity – we expect attenuation from joint compliances

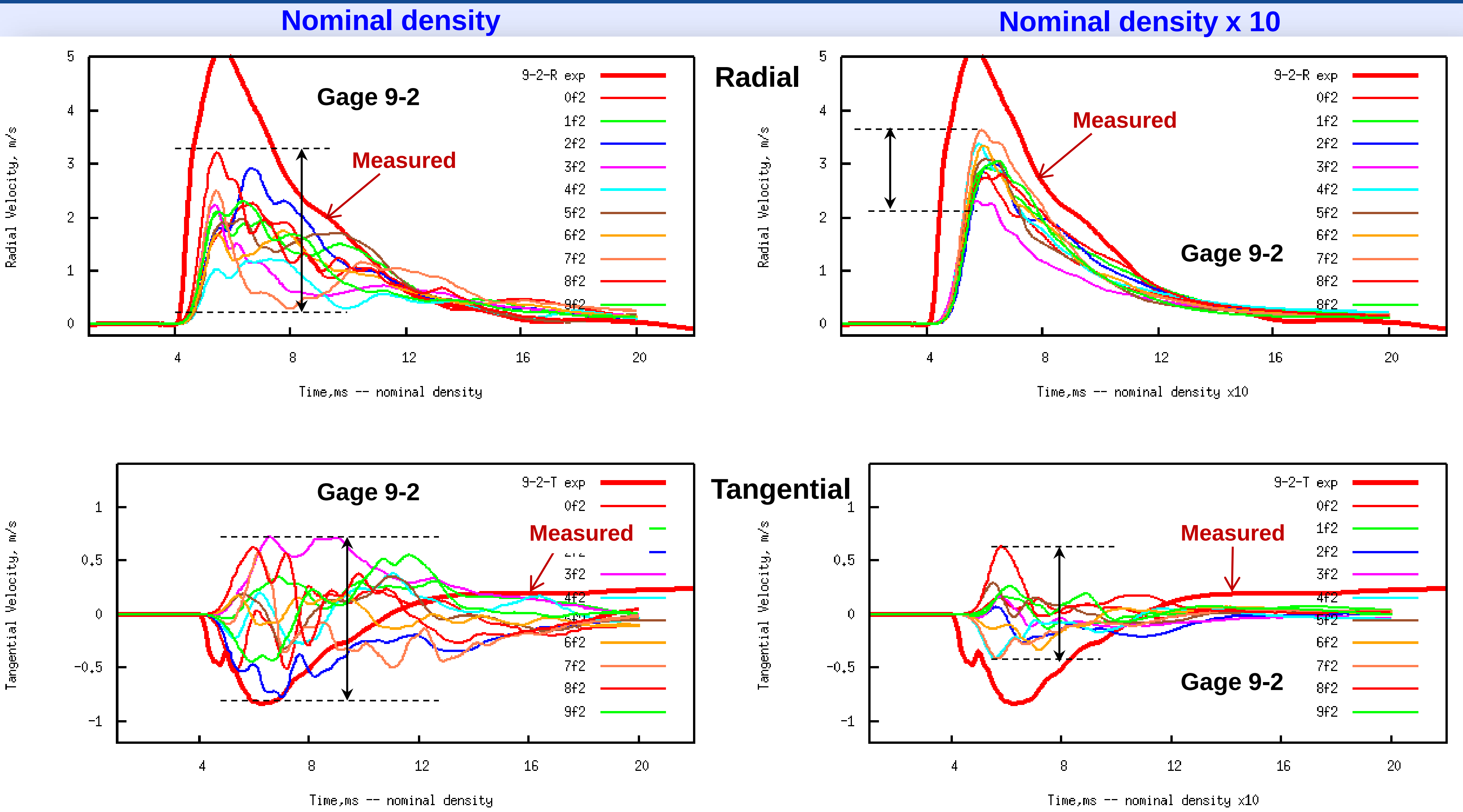
UQ analysis: double layer model –
Tangential velocity statistics based on 40 MCS

Shallow gages | **Middle gages** | **Deep gages**



Interestingly observed data lays with 95%CI of the simulations – bias to upper CI – joint compliances will shift the mean thus CI – note that the polarization is captured in several gages

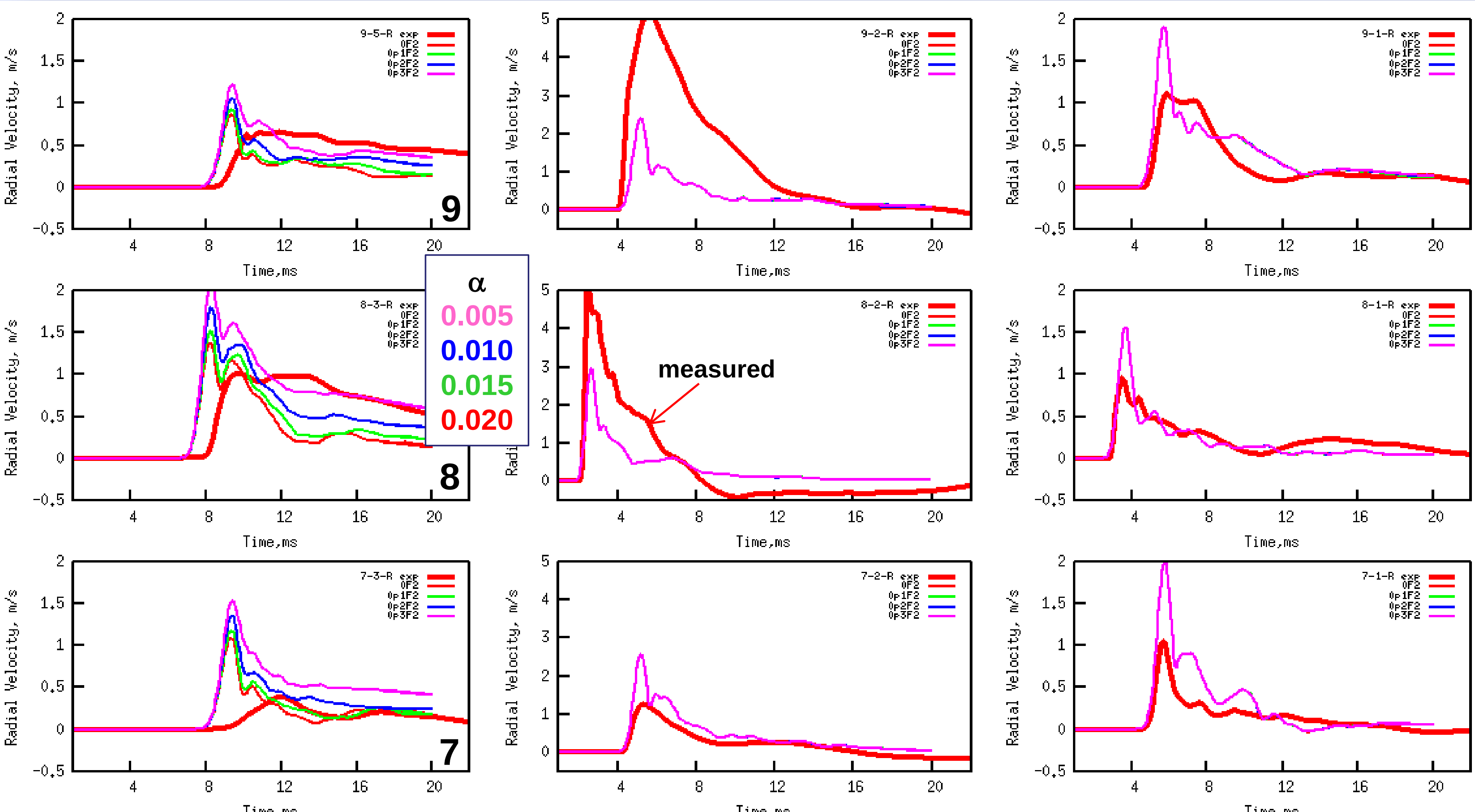
Sensitivity Analysis:
Effect of joint density on velocities



Increasing the density of joints leads to a decrease in velocity fluctuations (spread)
Increasing the density of joints leads to more "homogenized" rock mass

Sensitivity Analysis:
Effect of poro-elasticity of top layer – Radial velocities

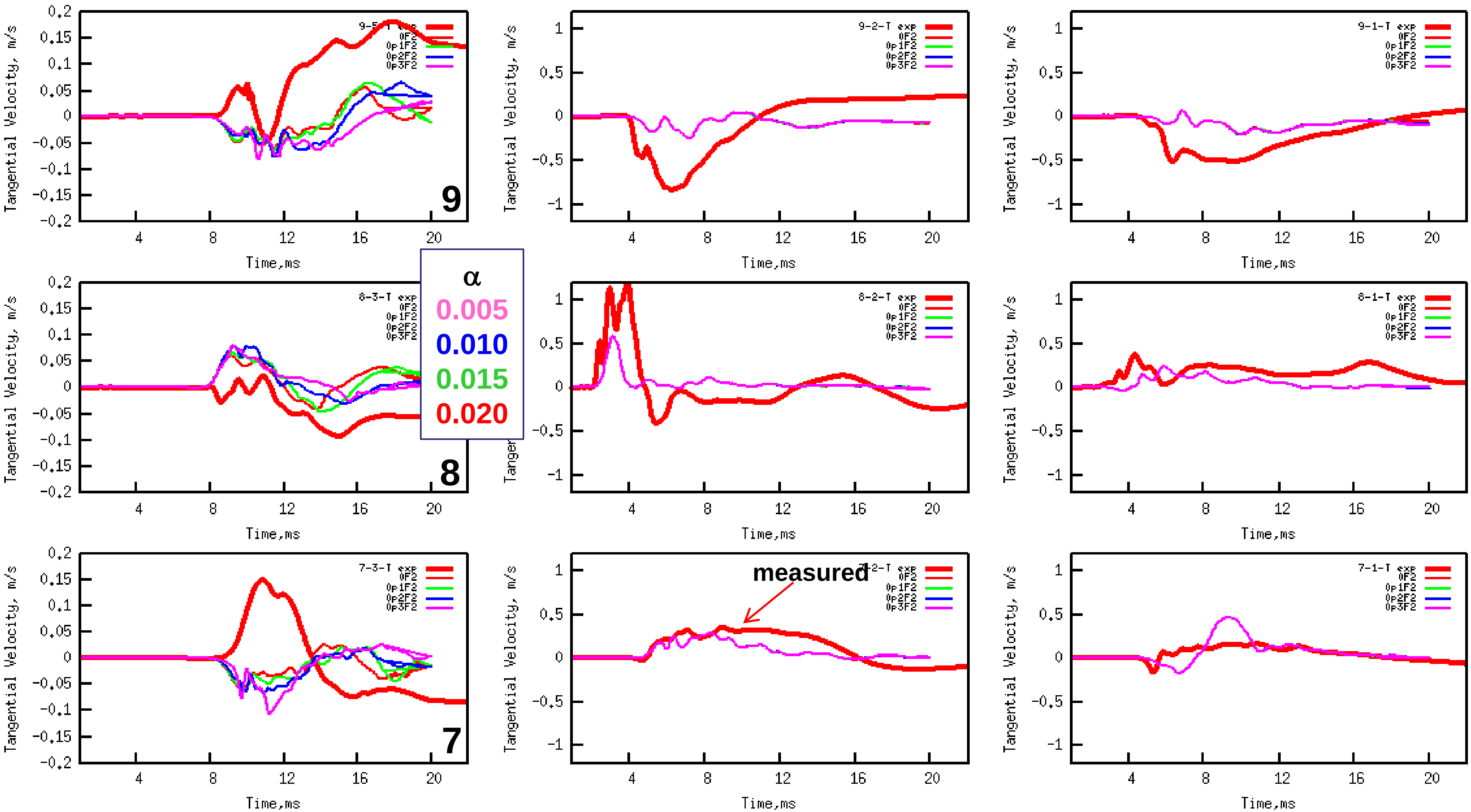
Shallow gages | **Middle gages** | **Deep gages**



Reducing the top layer poroelastic parameter leads to amplifying the velocities at shallow gages

Sensitivity Analysis:
Effect of poro-elasticity of top layer – Tangential velocities

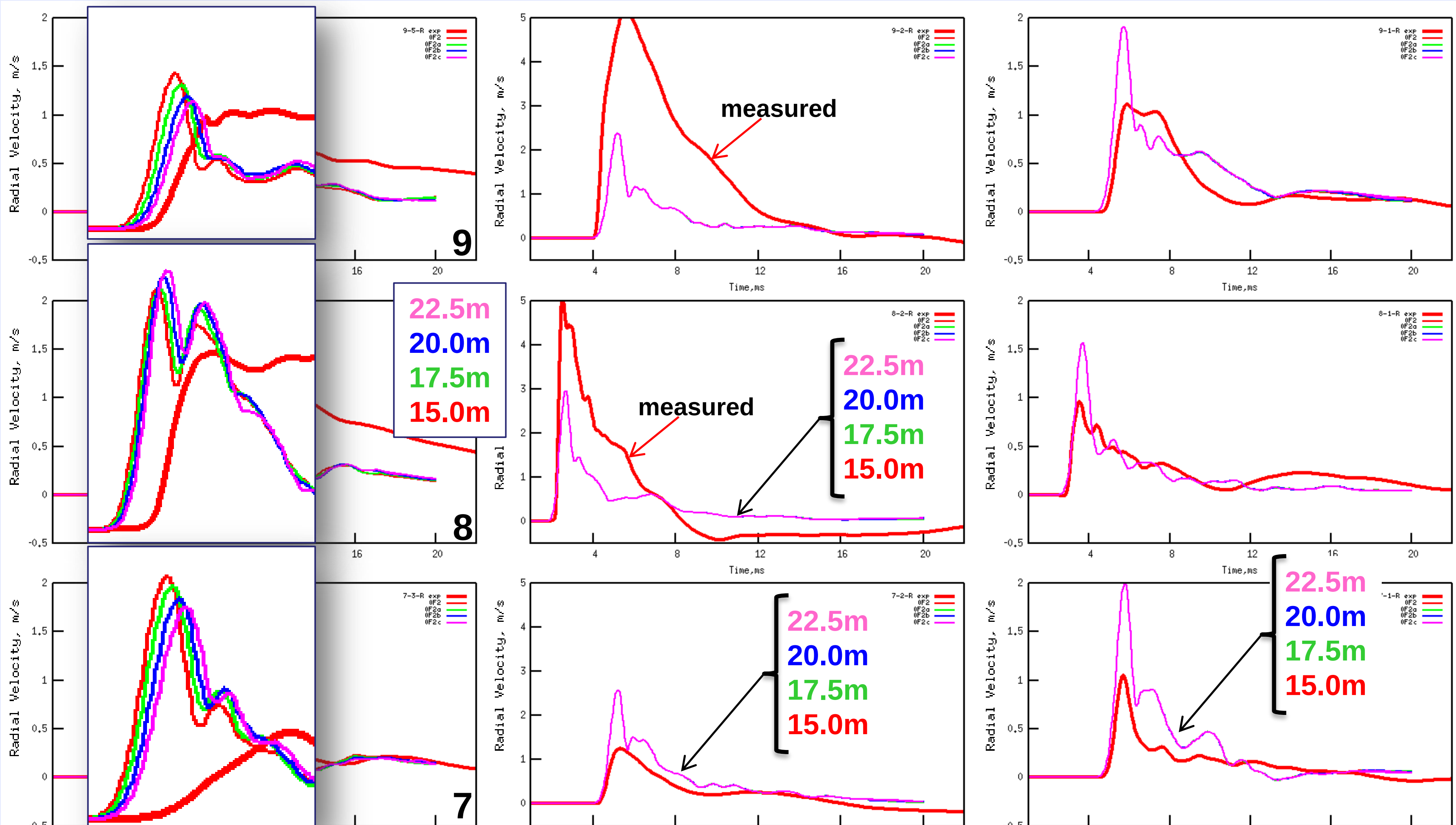
Shallow gages | **Middle gages** | **Deep gages**



Reducing the top layer poroelastic parameter impacts the velocities at shallow gages

Sensitivity Analysis:
Effect of thickness of top layer – Radial velocity

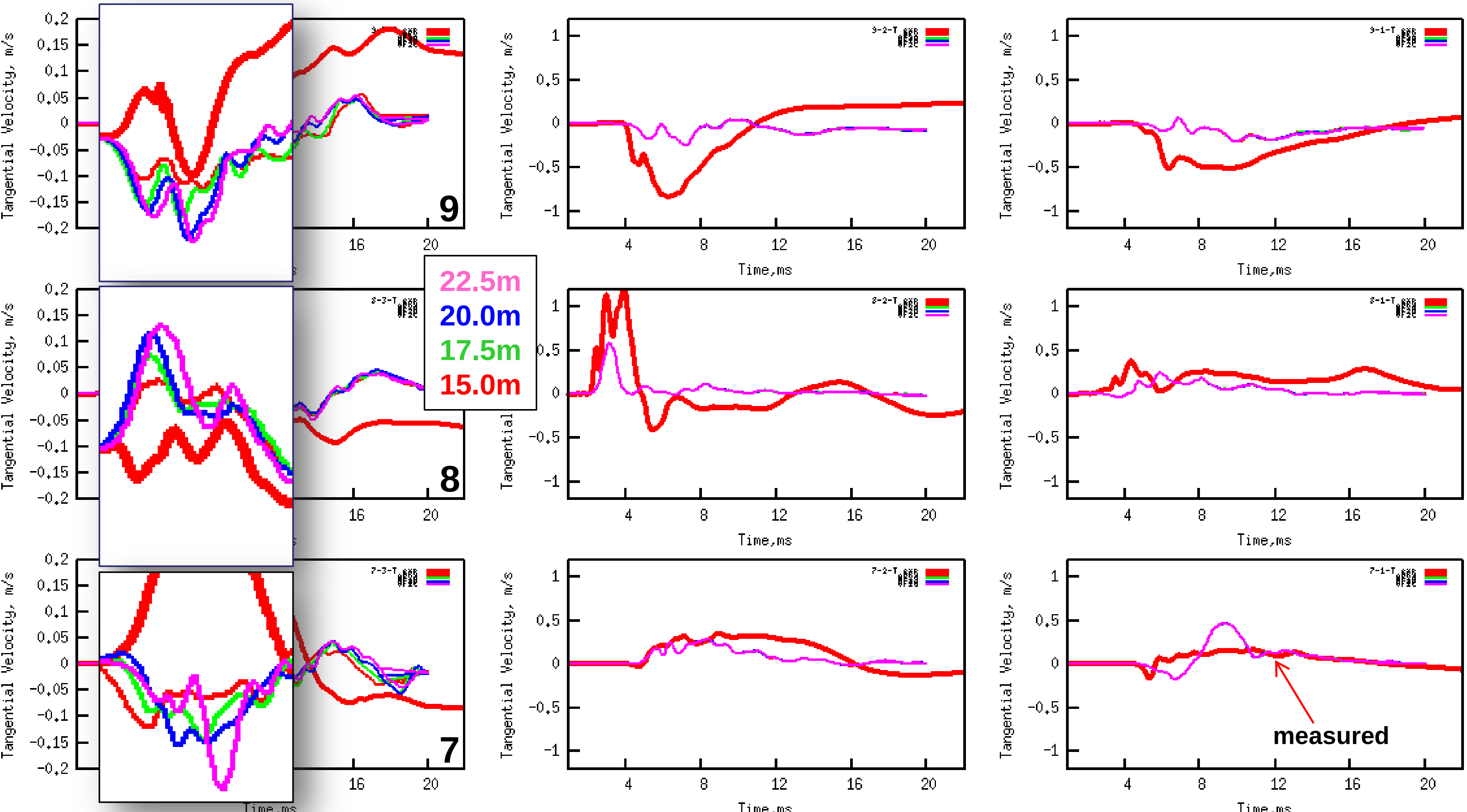
Shallow gages | **Middle gages** | **Deep gages**



Thickening the top layer impacts arrival times at shallow gages while deeper gages remain unchanged

Sensitivity Analysis:
Effect of thickness of top layer – Tangential velocity

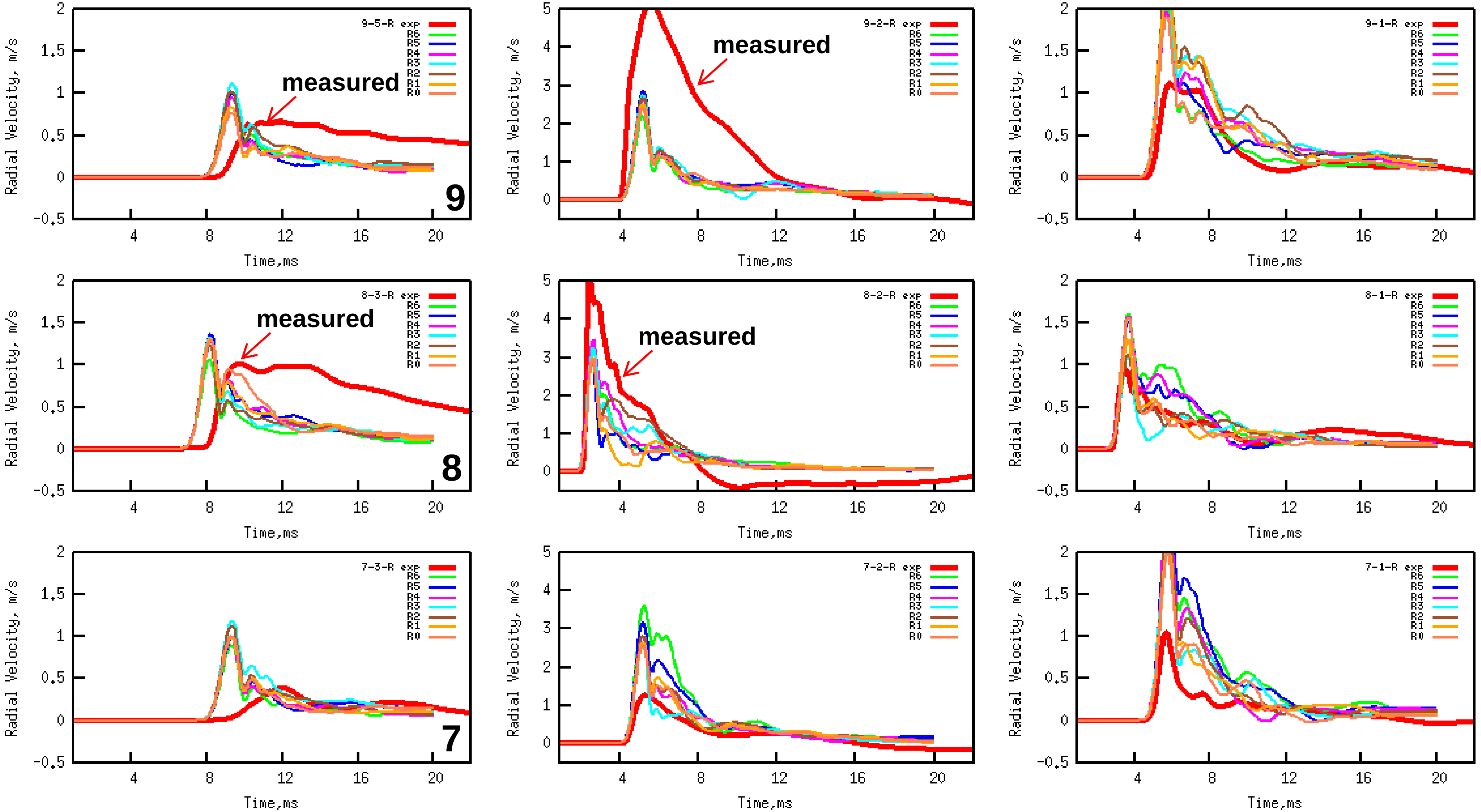
Shallow gages **Middle gages** **Deep gages**



Thickening top layer leads to amplifying the velocities at shallow gages -- deeper ones remain unchanged

Sensitivity Analysis:
Effect of joint orientation on radial velocity

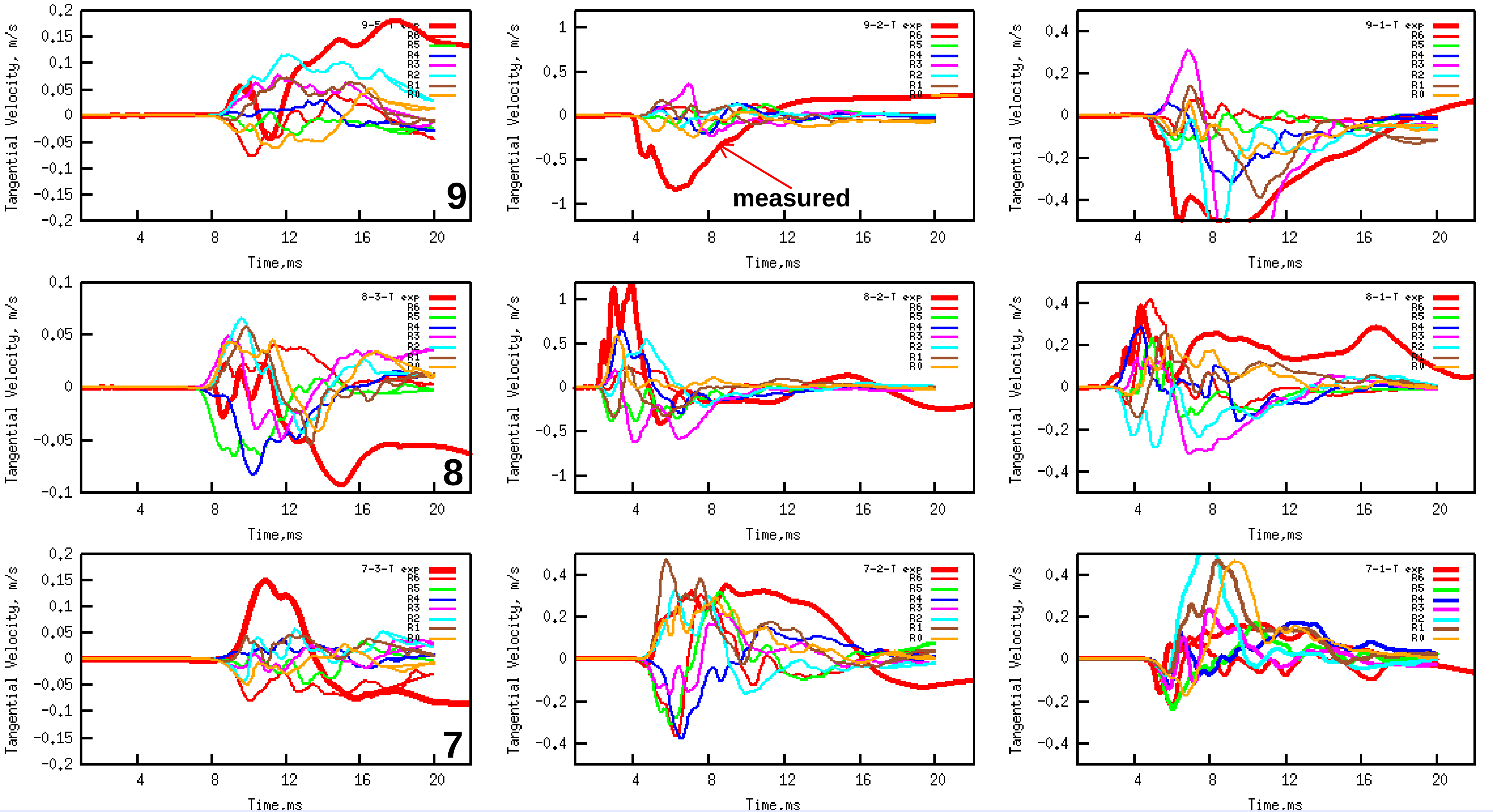
Shallow gages | **Middle gages** | **Deep gages**



Re-orientation of vertical set of joints can amplify the spread of velocities and their peak magnitude

Sensitivity Analysis:
Effect of joint orientation on tangential velocity

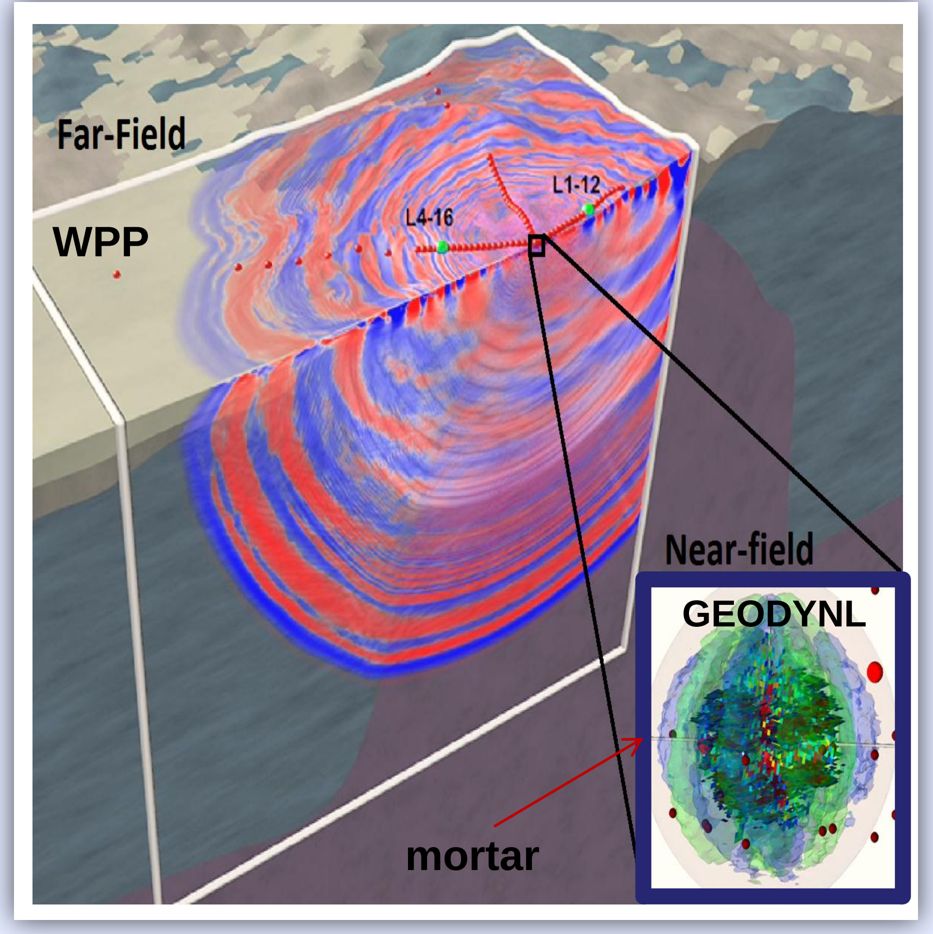
Shallow gages | **Middle gages** | **Deep gages**



Joint orientation of vertical set of joints leads to polarization switch in tangential velocities – joint compliances may lead to correlation between polarization and rotation angle of joints.

Far Field Monitoring Implications: Do joints nearby the source impact far-field signatures?

- **One-way coupling** between nonlinear, inelastic near-field and linear, visco-elastic far-field regions using a padding mortar space in 3D.
- **Near-field:** 3D Lagrangian hydrodynamics code with non-linear material response (GEODYN-L)
  - Explosion loading
  - Compressional and tensile failure, yielding, porosity, cavity formation
  - source mortar embedded within finite difference model
- **Far-field: 3D-FDM (WPP)**
  - Driven by interpolated time series from GEODYN model
  - Signals propagated through complex 3D velocity model of geology to distances of 10's of kms
  - Coupling verified and validated.

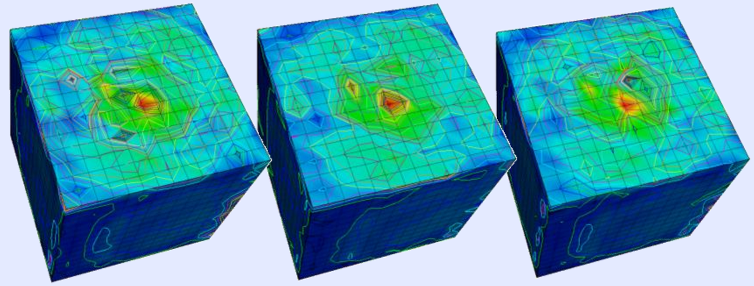


WPP

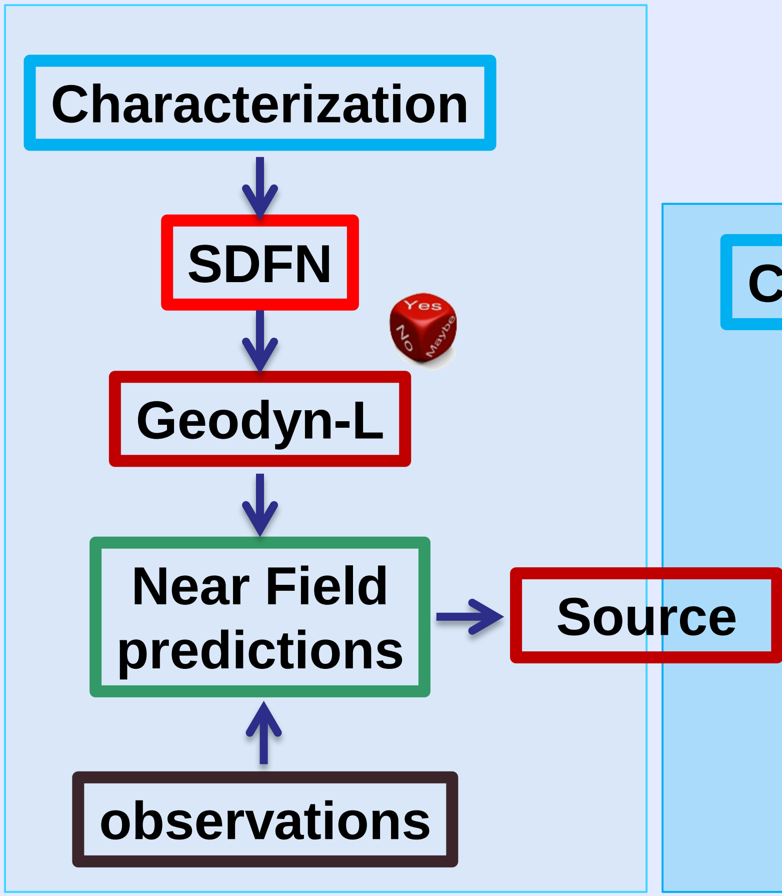
3D finite-difference code Curvilinear grid for topography, mesh refinement, viscoelastic model .Designed for massively parallel systems

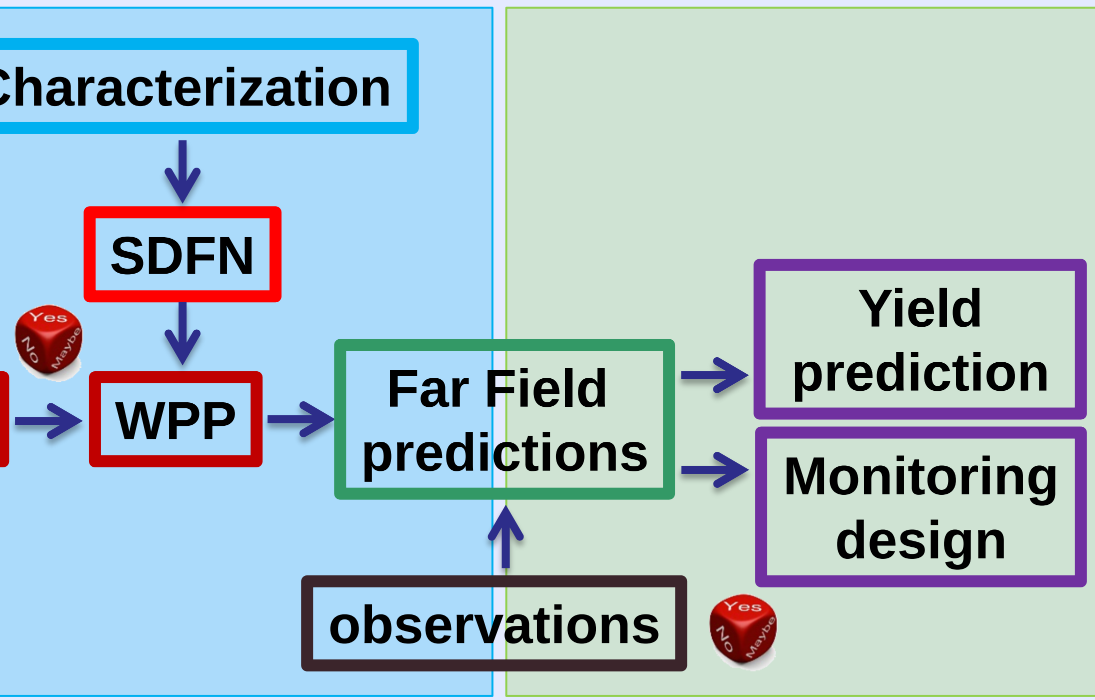
Uncertainty propagation to far field monitoring receivers: source abstraction and WPP simulations

Flow chart of UQ propagation and estimation for SPE



Examples of 3 equally probable sources for far field propagation

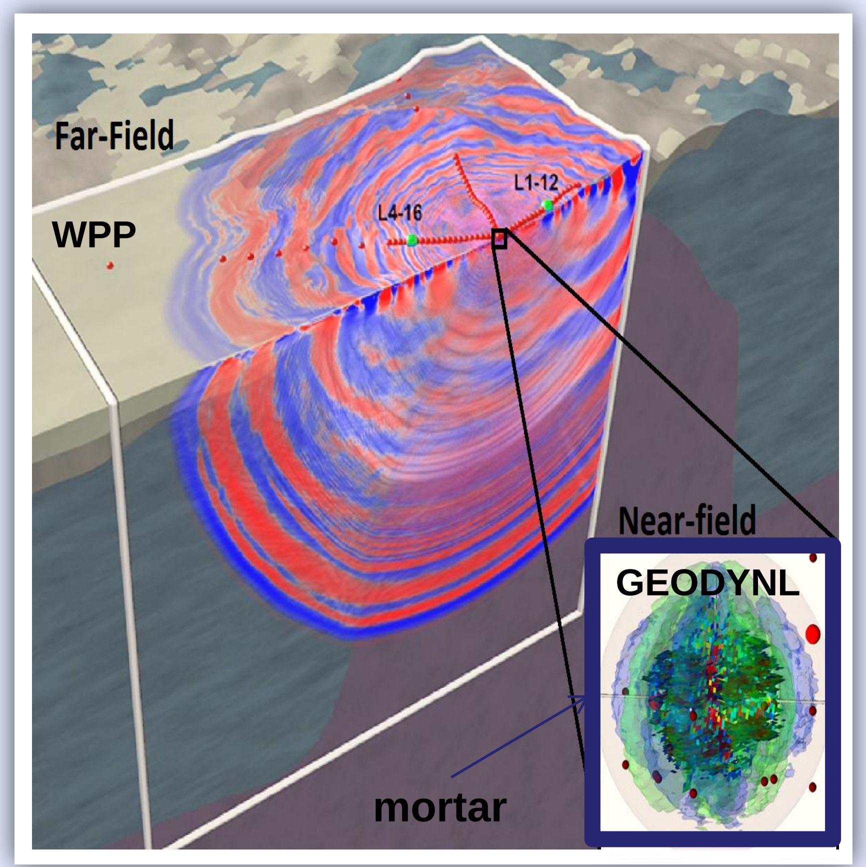




Our ultimate goal is to estimate yields and design monitoring networks under conditions of uncertainty

Summary & Path forward

- **Summary:**
  - A UQ framework has been established and streamlined with SPE from end-to-end analyses
  - Several UQ & SA studies have been conducted
  - Joints affects significantly near field motions, impacts on far field motions are been explored
  - Vertical joints can lead to horizontal motion (persistence throughout MCS and their stats)
  - Friction angle and joint density (thus spacing) affect shear motions
  - Joint compliances will attenuate the peak velocity and will increase pulse spread
- **Path forward:**
  - Assess the impact of joint compliances on velocities
  - Propagate UQ to Far Field receivers
  - Help with SPE4 and SPE5 designs
  - Design a monitoring network based on uncertainty
  - Design a yield estimator under conditions of uncertainty
  - Global sensitivity (what does really matter)



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Auspices

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